# Large Liquid Cherenkov Ring Imaging Detector Reconstruction Algorithms

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*2012 Project X Physics Study*
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- Physics Opportunities with large Water Cherenkov detectors
- Current examples
    - Super-Kamiokande
    - MiniBooNE
    - For LBNE, see M. Wetstein and S. Seibert's talks
- Future Possibilities

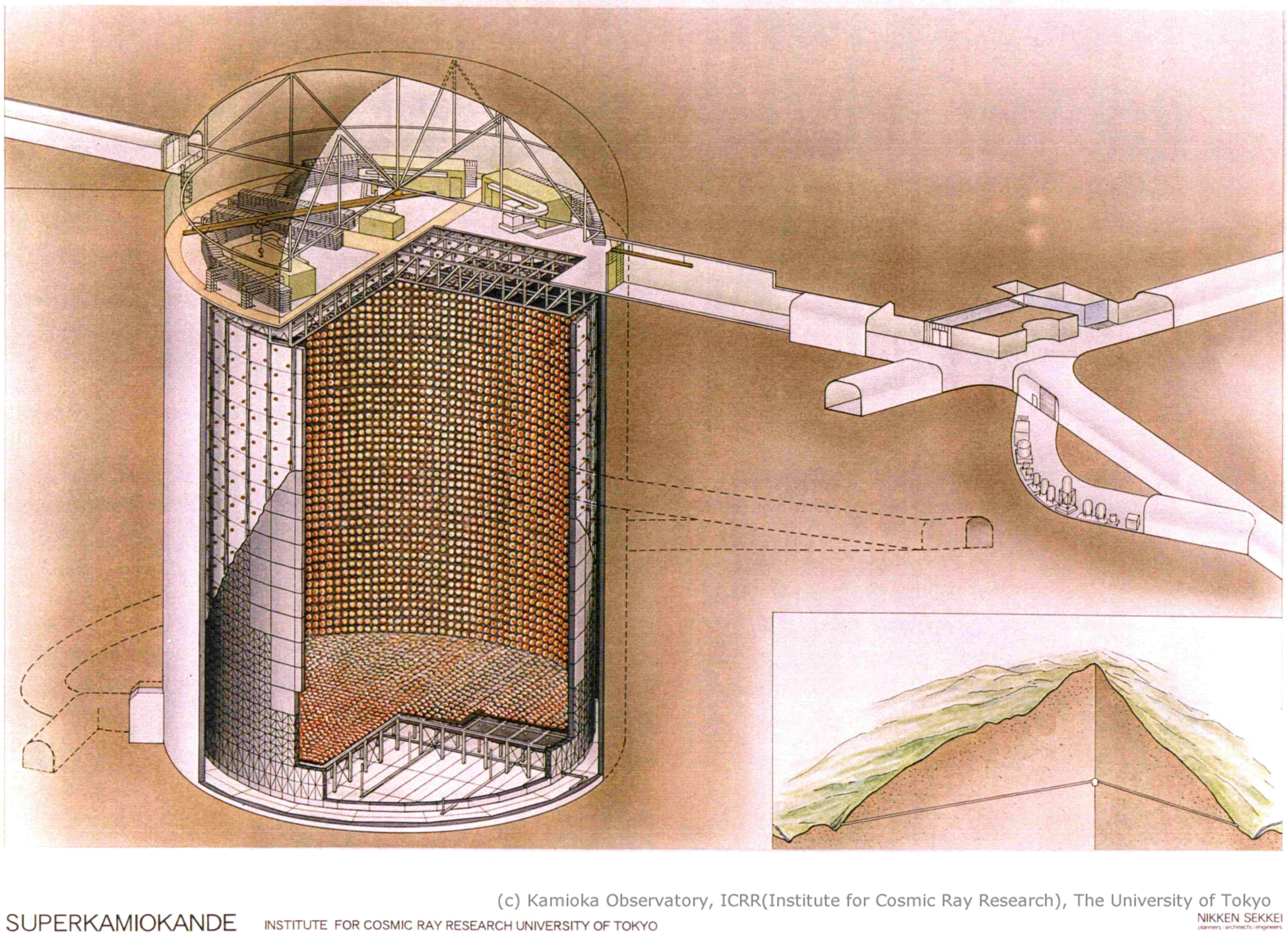
# Physics Opportunities with Large Water-Cherenkov Detectors

Critically depends on ability to measure $\nu_e$ appearance in a predominantly $\nu_\mu$ beam

- Neutrino Oscillation Measurements
  - $\sin^2(2\theta_{13})$ -- it's already measured by Daya Bay, RENO, T2K, Double Chooz and others, but additional precision and consistency tests are valuable (new physics)
  - Mass Hierarchy
  - Measurement of $\delta_{CP}$
  - Non-Standard Interactions
- Atmospheric Neutrino Oscillation Measurements
- Supernova Burst Neutrinos
- Relic Supernova Neutrinos
- Nucleon Decay
- Neutron-Antineutron Oscillations

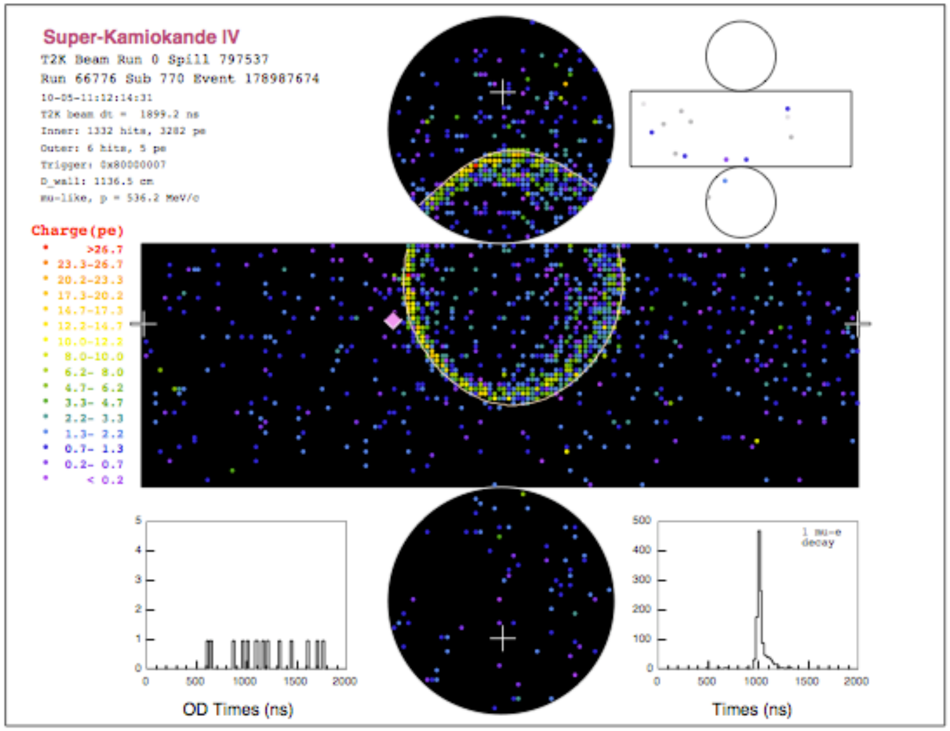
# The Super-Kamiokande Detector

Located 1 KM underground.  50 kTons of water; 11,129 50-cm PMT's facing inwards
40% photocathode coverage

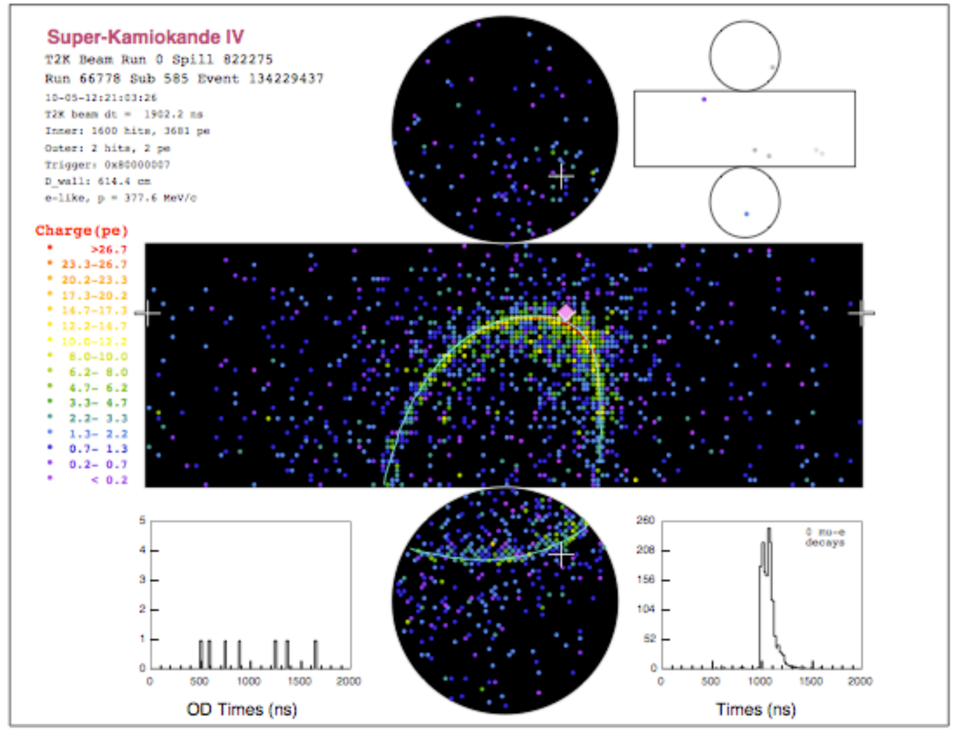



1,885 20-cm PMT's facing outwards (veto)

# Sample T2K Events in Super-Kamiokande IV




(a) muon-like event

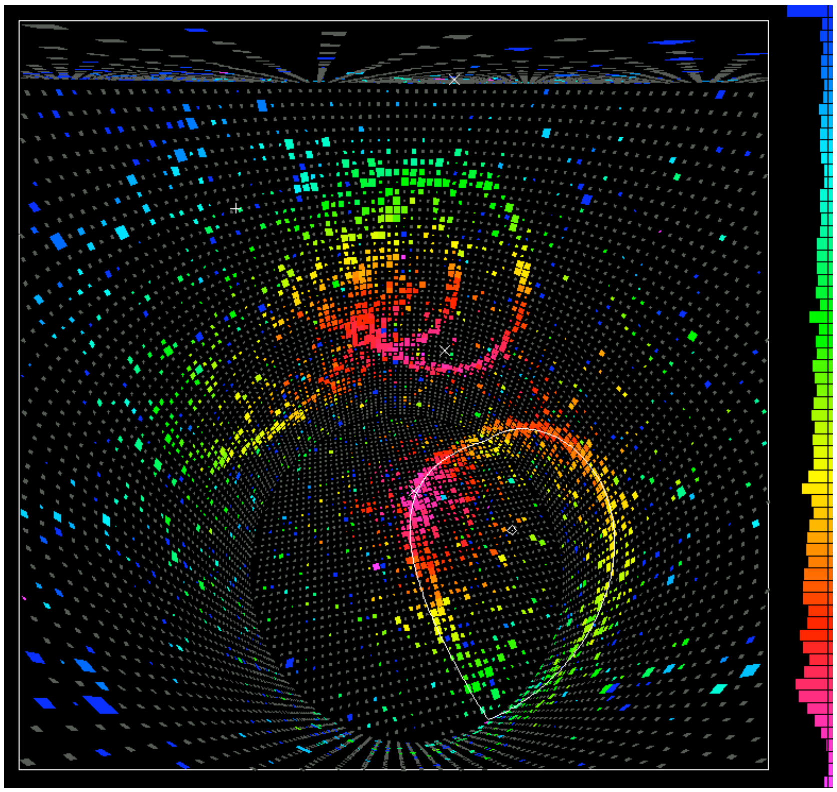



(b) electron-like event

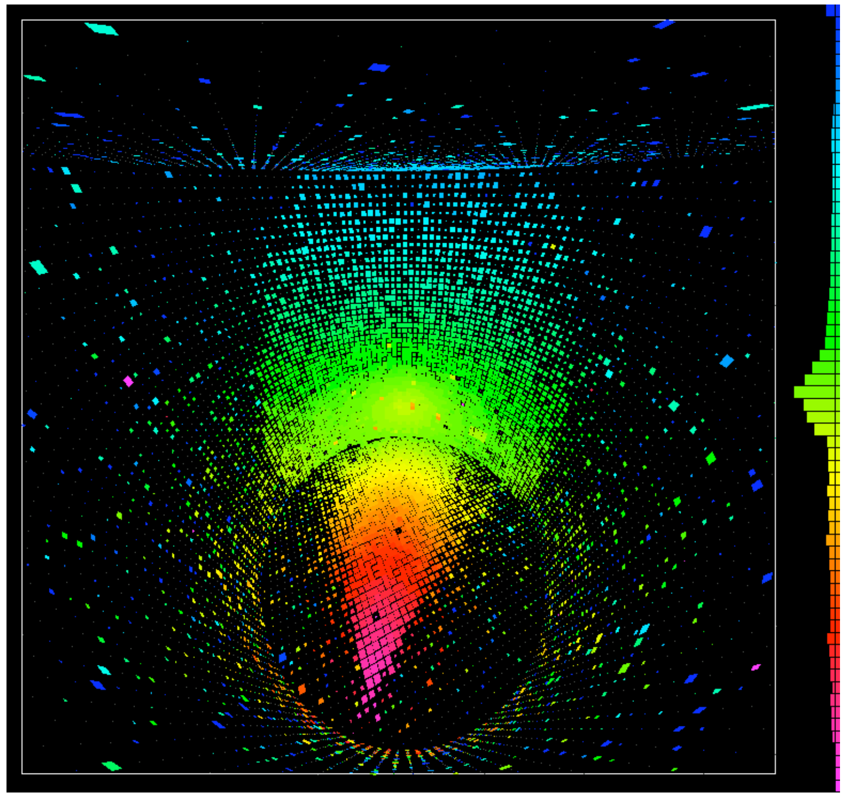
From the T2K NIM article: K. Abe et al., NIM A **659**, 106 (2011)
arXiv:1106.1238v2

# Typical Events in Super-Kamiokande

Multi-ring event.
Almost a proton decay candidate, failed some analysis cuts. Found by Brett Viren.



Throughgoing Cosmic Ray



# SK Reconstruction Overview

References:

- M. Shiozawa, “Reconstruction algorithms in the Super-Kamiokande large water Cherenkov detector”, NIM A **433**, 240 (1999).
- SK Collaboration, “A measurement of atmospheric neutrino oscillation parameters by SK-1”, Phys Rev. D **71**, 112005 (2005).
- SK Collaboration, “Kinematic reconstruction of atmospheric neutrino events in a large water Cherenkov detector with proton identification” PRD **79**, 112010 (2009).
- T2K Collaboration, “The T2K Experiment”, NIM A **659**, 106 (2011).
- See also Kimihiro Okumura’s talk at ANT11 on POLFIT optimization for reduction of $\pi^0$ background. https://indico.fnal.gov/conferenceDisplay.py?confid=4887

All reconstruction amounts to maximizing L(data|event parameters)

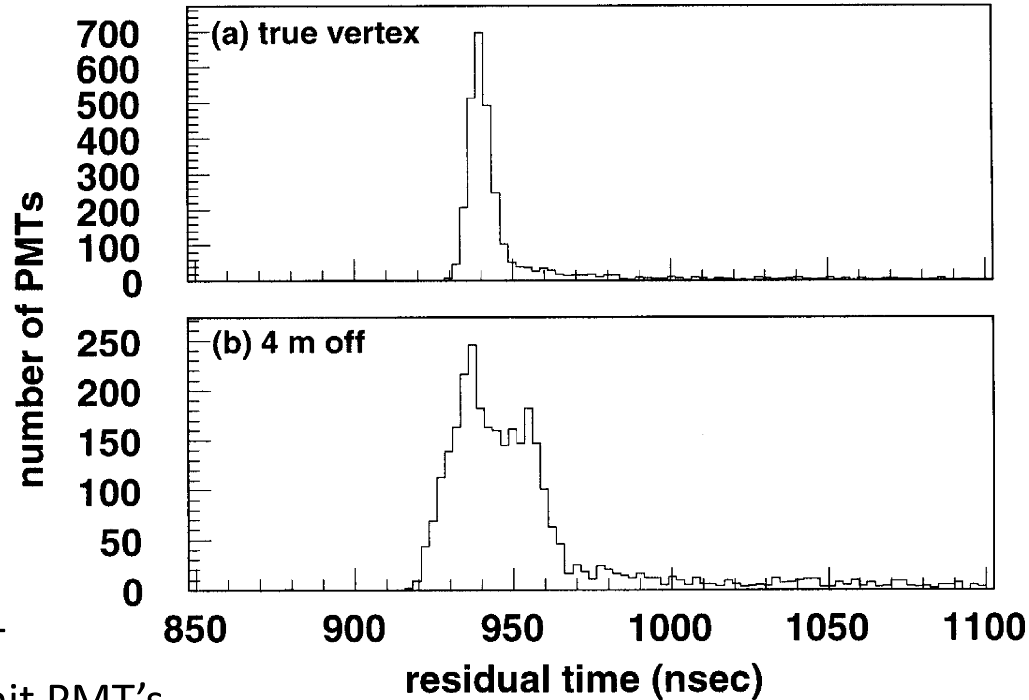
Algorithms are designed to factorize the problem in pieces that can be solved reliably.

## Reconstruction Steps:

1) Vertex fit
2) Ring identification (Hough Transform)
3) Particle ID
4) Multi-Ring Separation
5) Momentum Determination

# SK Vertex Fit

$$G = \sum_i \frac{1}{\sigma_i^2} \exp\left( - \frac{(t'_i - t_0)^2}{2(\langle\sigma\rangle \times 1.5)^2} \right)$$




$i$ indexes the hit PMT

$\sigma_i$ is the timing resolution of the $i^{th}$ PMT

$\langle\sigma\rangle$ is the average resolution over the hit PMT's

$t'_i$ is the TOF-subtracted time, including the track length

$G$ is a likelihood function and $t_0$ is chosen to maximize it

Resolution (1999, MC):

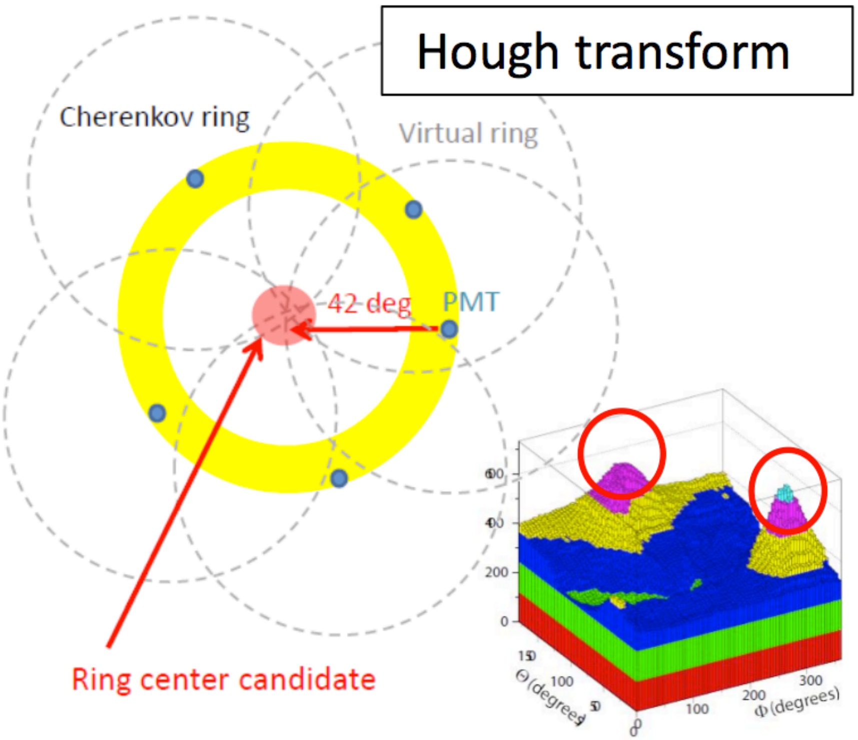
18 cm for $p \rightarrow e^+ \pi^0$.

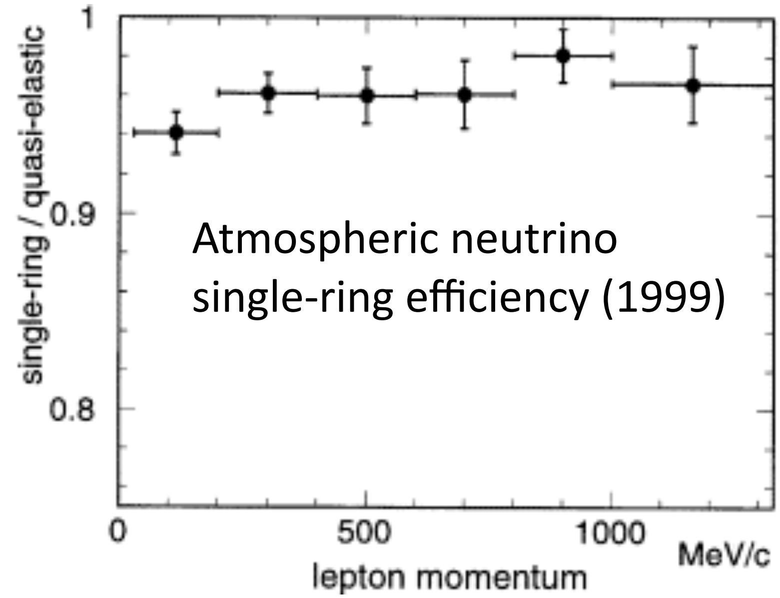
34 cm for single-ring electron events

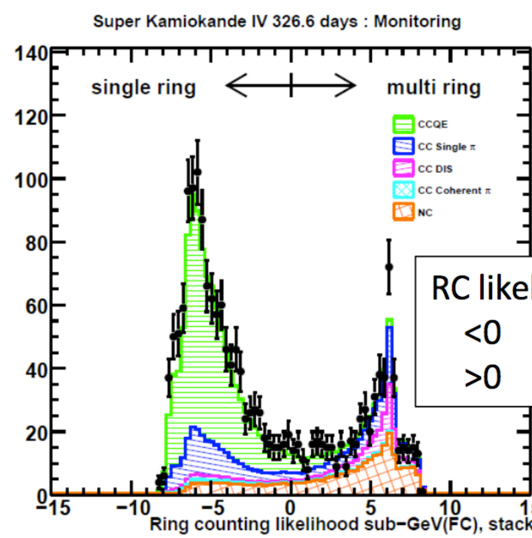
25 cm for single-ring muon events

M. Shiozawa, NIM A **433**, 240 (1999).

# Ring Finding – Hough Transform



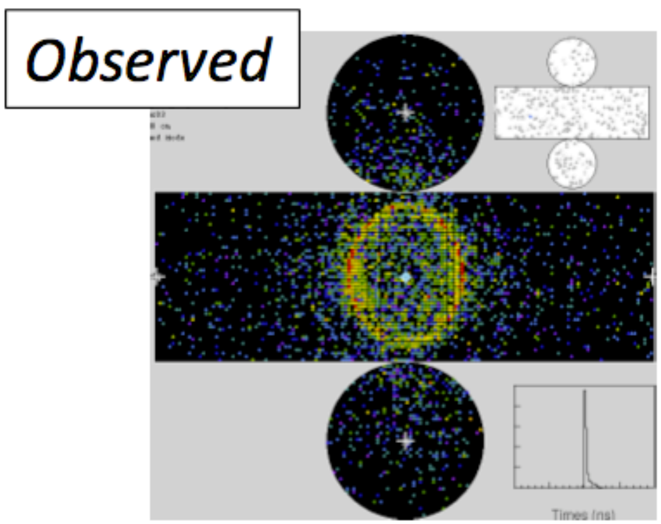

RC likelihood of atm ν
<0 single-ring
>0 multi-ring

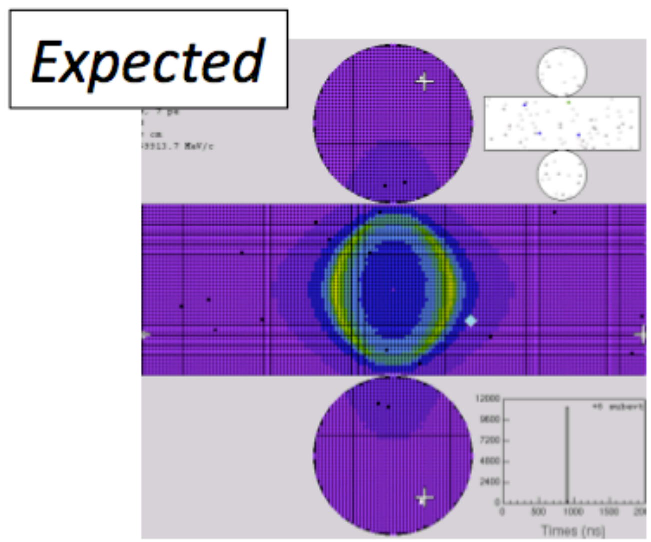
These days, count rings with the Hough transform, and check with a likelihood function

# Particle ID

Comparison of observed patter of light with that expected for an electron-like or muon-like ring.

- Expected charge pattern can be generated with inputs of *vertex, direction, energy, particle-ID*
- Expected light consists of *direct light* and *scattered light*
- Direct light: *look up table* (generated from MC) by PID, momentum, distance to PMT, $\cos\theta$ (Cherenkov opening angle)



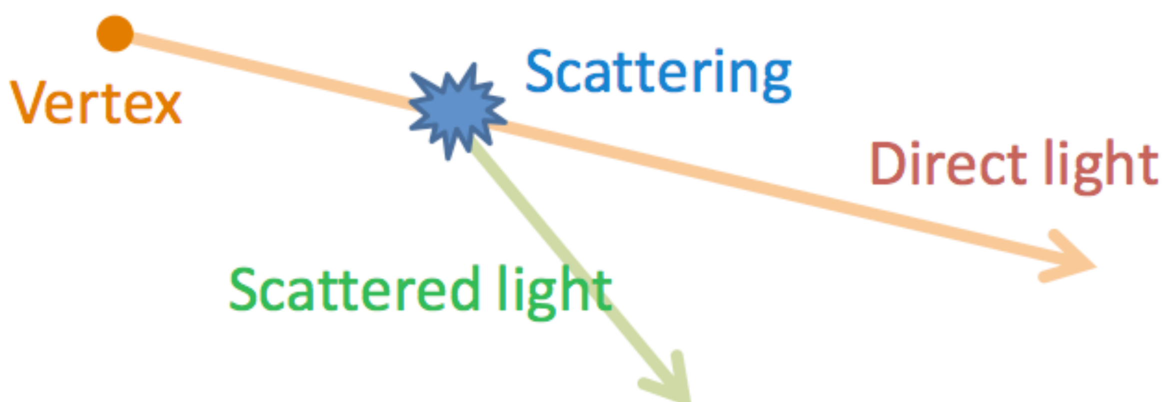




Slide taken from K. Okumura ANT11

# Scattering light calculation

- Along a path of direct light from vertex, scattering is calculated and its amount is integrated
- This integration is done for all direct light directions
- Attenuation in water and scattering angle are considered
- Calculation is based on coarse “patch” group

Slide taken from K. Okumura ANT11

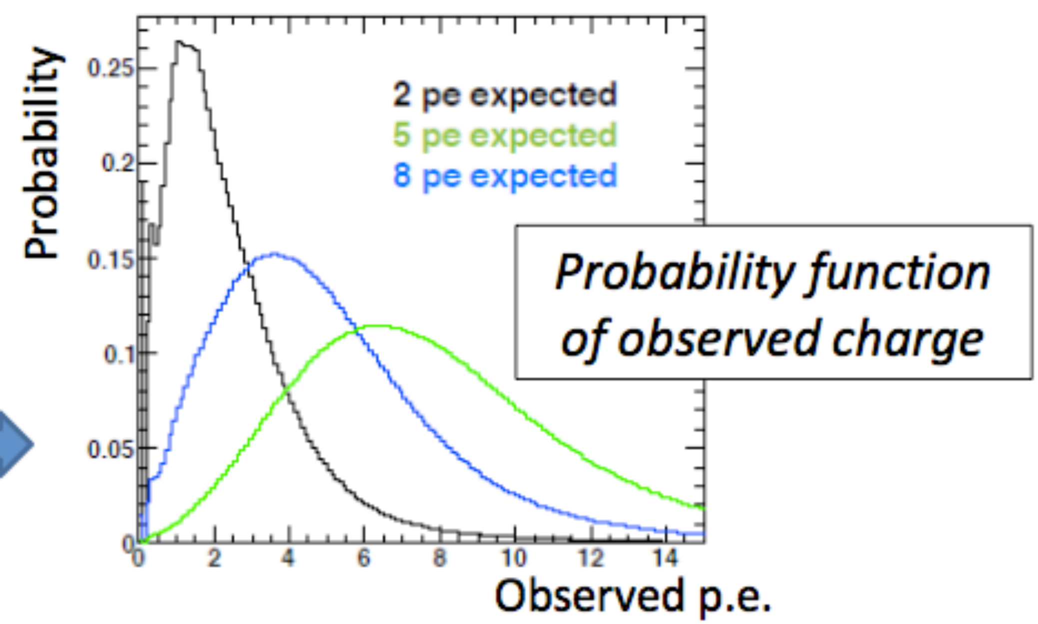


# POLfit Likelihood

- For each expected light pattern, a *likelihood* is generated by comparing that pattern to the observed pattern.
- *Probability function* based on measured single photo electron distribution of real PMT is used
- This likelihood function is fed into *MINUIT minimizer*

*Likelihood :*

$$\mathscr{L} = \sum_{PMT} \underline{\ln \mathrm{Prob}(Q_{\exp}, Q_{obs})}$$

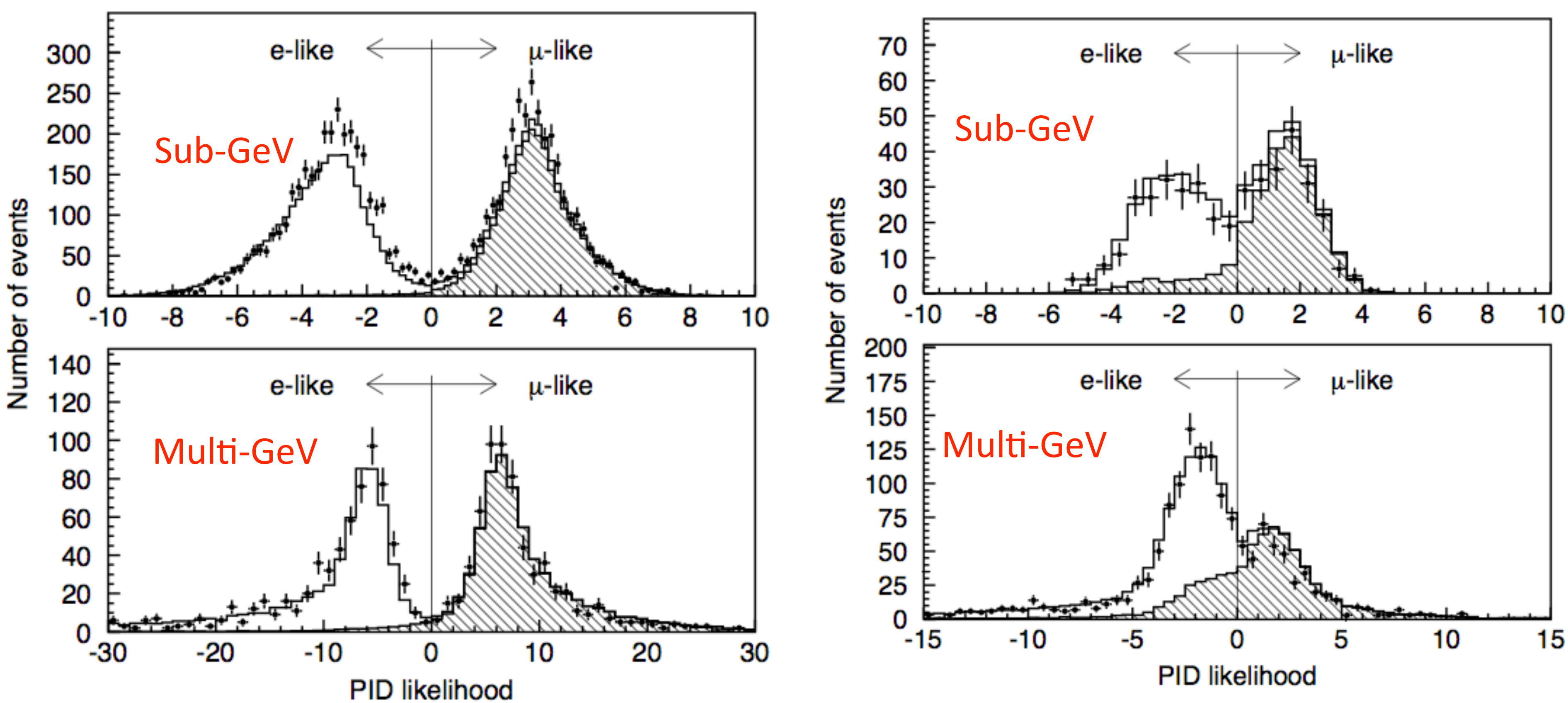



Slide taken
from K. Okumura
ANT11

# Particle ID Likelihood Separation – e vs μ

Single Ring Events

Multi-Ring Events




PRD 71 112005

# POLfit – e vs. $\pi^0$ Separation Algorithm

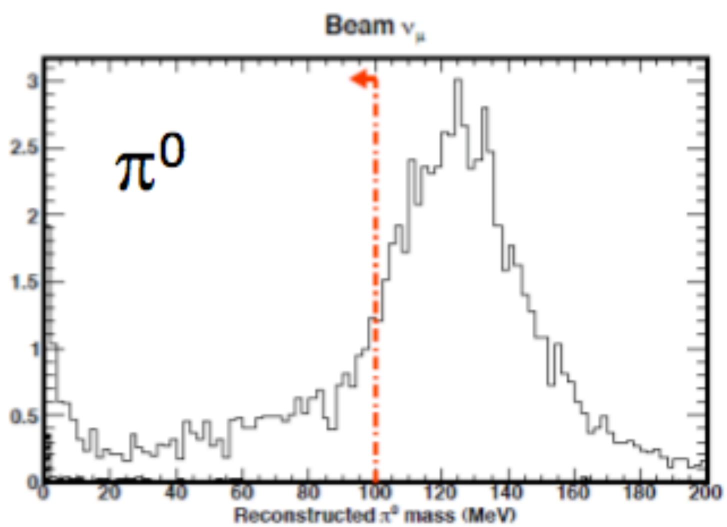
1. INPUT: one found ring direction, vertex, and total charge (given by std. reconstruction)
2. Assuming there should be *two gamma rings*, search for a second ring
3. Assuming 2nd ring direction and energy, *generate expected light pattern* of 2-ring event.
4. *Compare* this pattern to observed. This is *iterated* until optimal 2nd ring location and energy are found.
5. Return *$\pi^0$ invariant mass* from optimal values
6. Also do comparison with 1R e-like assumption, and return *likelihood difference* between 1R e-like and 2R $\pi^0$-like.

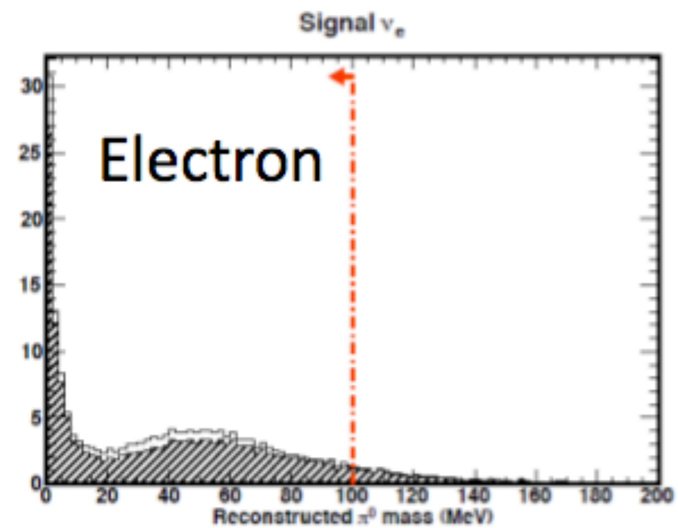
Slide taken from K. Okumura ANT11

# POLfit output

- After minimization, *momentum of both two rings* and *2nd gamma direction* are obtained
- *Invariant mass* is constructed using this output. This is used as discrimination parameter between electron and $\pi^0$
- Backgrounds have a peak around $\pi^0$ mass (~135MeV). Can reject them by <~100 MeV/c cut.

*Reconstructed invariant mass by POLfit*



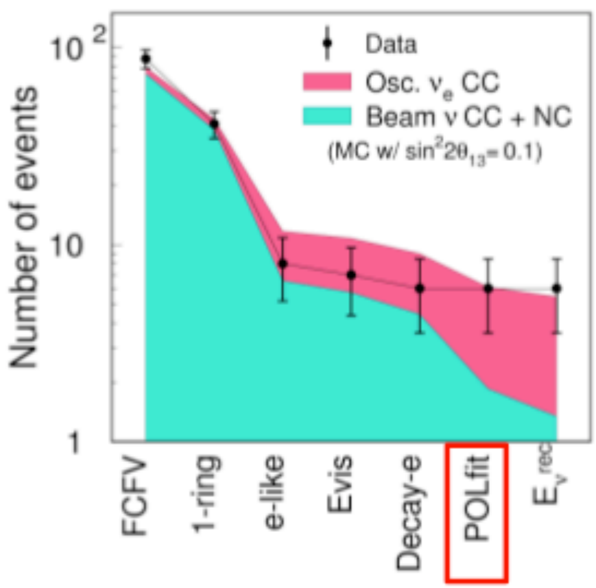




Slide taken from K. Okumura ANT11

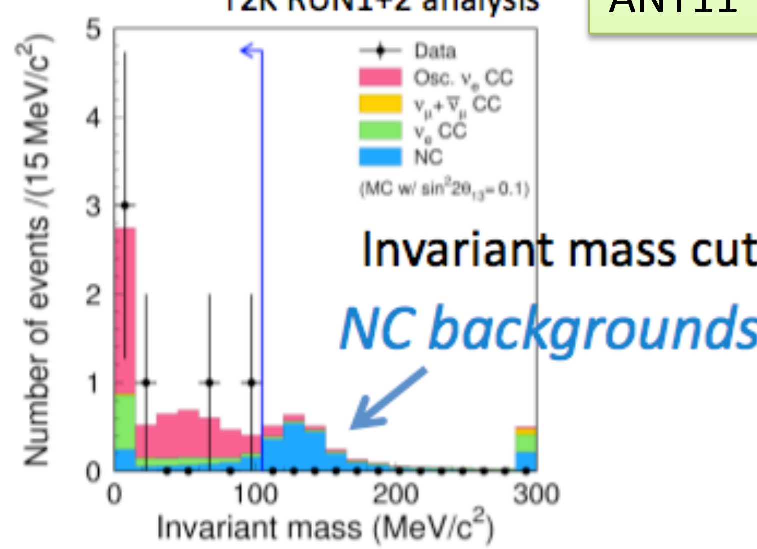
# POLfit performance in T2K analysis

- Invariant mass cut is applied after 1-R e-like selection
  - *Optimize cut criteria by MC : $M_{inv} < 105$ MeV/$c^2$*
- *Significant reduction* for NC backgrounds
  - *~95% $\pi^0$ rejection, 66% signal acceptance achieved by all cuts*
- NC $\pi^0$ is no more most significant background
  - *amount of NC BG is less than beam intrinsic $\nu_e$ in T2K*

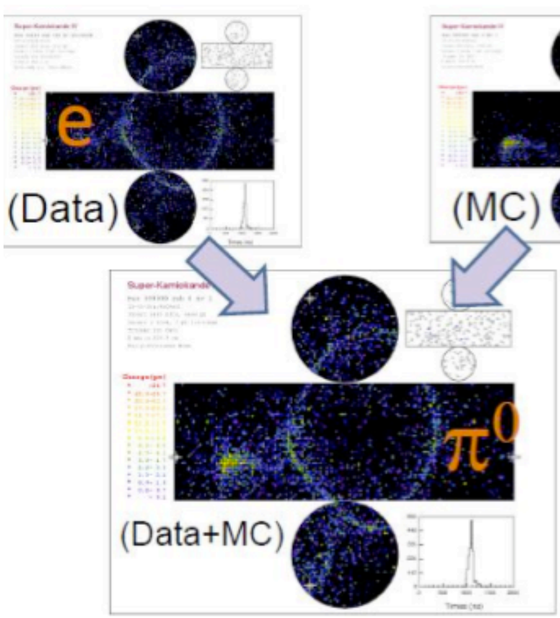
Slide taken from K. Okumura ANT11

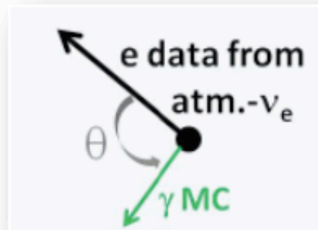



T2K RUN1+2 analysis



# Calibration of e-$\pi^0$ Separation Algorithm




Composite event sample with *electron data* and *gamma MC*

Electrons are taken from *atm. ν* and *cosmic Michel electron*

Can estimate *systematic uncertainty* coming from ring where electron is used

Apply T2K $\nu_e$ selection and *compare cut efficiency* between control sample data and its MC

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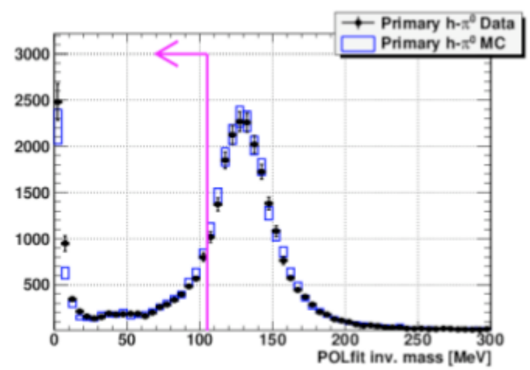
Invariant mass of h-$\pi^0$ Data/MC




*Data/MC diff. after cut selection:*
*7.8 % in primary sample*
*4.3 % in secondary sample*
*by taking quad. sum, 10.8% error estimated for amount of $\pi^0$ BG (considering stat. uncertainty of sample)*

Slides taken from K. Okumura ANT11

# Achieved Performance of Super Kamiokande Reconstruction

- Vertex resolution:
  18 cm for $p \rightarrow e^+ \pi^0$.
  34 cm for single-ring electron events
  25 cm for single-ring muon events

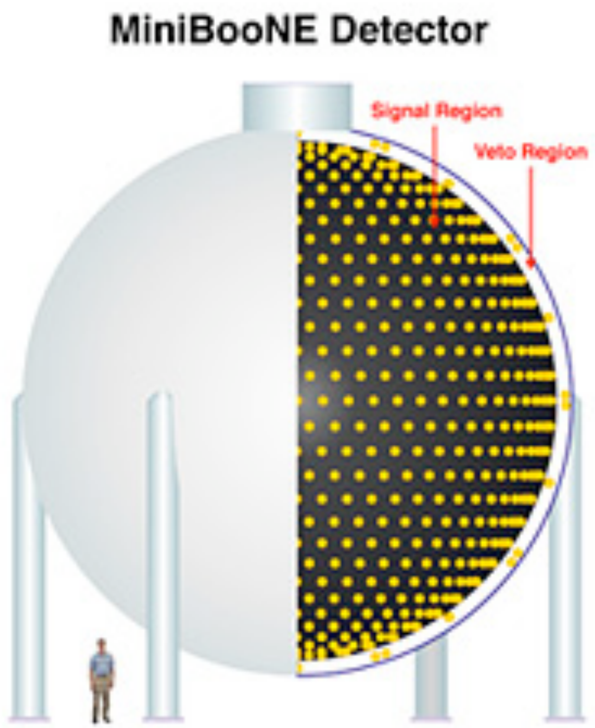
- Angular resolution: 3° (electron-like rings),
  1.8° (muon-like rings)

- CC QE efficiency: 93% (electron, single ring)
  96% (muon, single ring)

- Energy resolution for single rings
  - muons: ± (0.7/sqrt(E(GeV))+1.7)%
  - electrons: ±(2.6/sqrt(E(GeV)) + 0.6)%

- Background rejection: < 0.1% muons misID'ed as electrons,
  < 5% NC $\pi^0$'s misID'ed as electrons (From M. Shiozawa's talk on Saturday

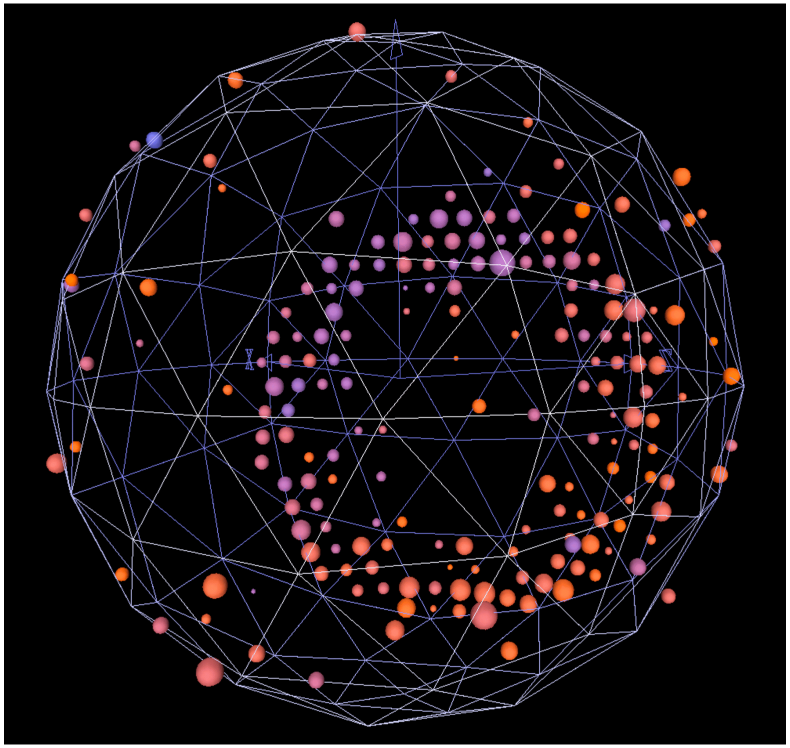
# MiniBooNE Experiment




6.1m radius sphere filled with minearal oil.

1280 inward-facing 8” PMT’s (5.75 m radius inner region)

240 outer PMT’s for veto

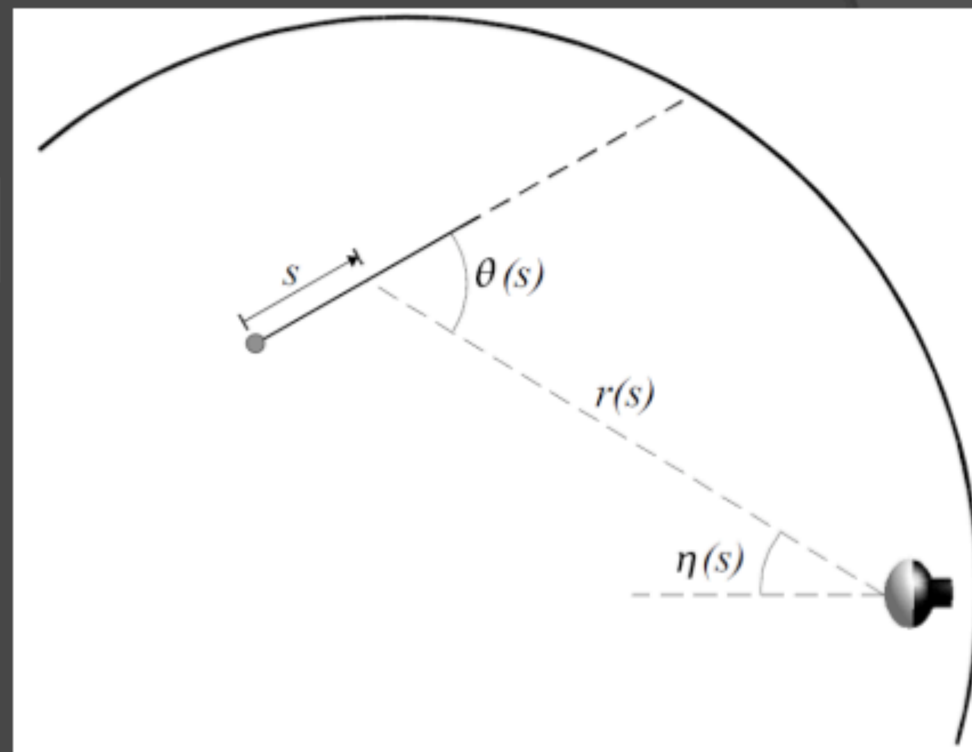


Direct and scattered Cherenkov light, plus scintillation light with a lifetime of 35 ns.

R. Patterson *et al.*, “The Extended-track Reconstruction for MiniBooNE”, NIM A **608**, 206 (2009).

# Track Fitting – Predicted Charge Extended Track Directional

$$\mu_{\rm Ch} = \Phi_{\rm Ch} \int_{-\infty}^{\infty} ds\, \rho_{\rm Ch}(s)\, \Omega(s)\, T_{\rm Ch}(s)\, \epsilon(s)\, g(\cos\theta(s); s)$$



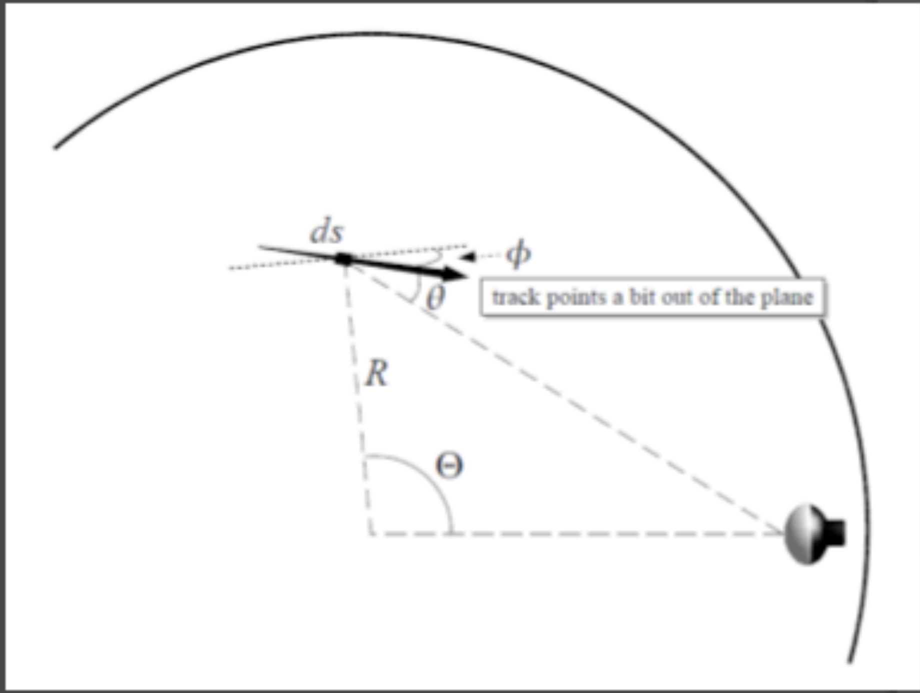

g(cos θ(s);s) – angular emission profile

Slide from M. Tzanov

# Track Fitting – Predicted Charge Indirect Light Directional Source

Scattering tables

$$A_{\mathrm{Ch}}(R, \cos\Theta, \cos\theta, \phi) \equiv \frac{d\mu_{\mathrm{Ch}}^{\mathrm{indirect}}}{d\mu_{\mathrm{Ch}}^{\mathrm{direct,iso}}}$$




Slide from M. Tzanov

# Similarities and Differences between SK and MiniBooNE Reconstruction

- MiniBooNE: Scintillation light significant and included in likelihood.
  SK: no scintillation

- MiniBooNE: Spherical detector geometry simplifies likelihood function lookup tables
  SK: Cylindrical geometry more complicated

- MiniBooNE: Include PMT's that are *not* hit in the likelihood function as well as
  hit PMT's. Adds information.

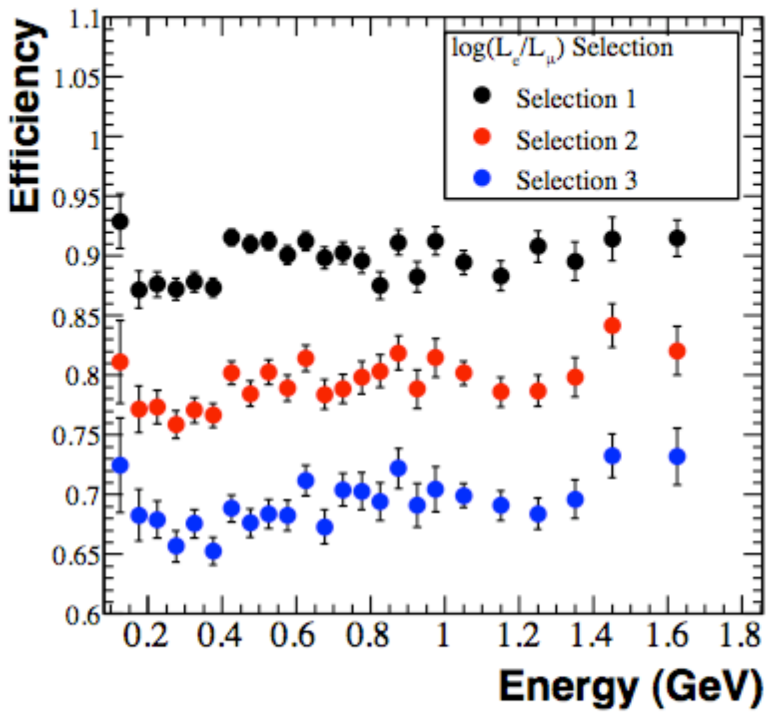
For larger detectors, there are more unhit PMT's. But computers always get more capacity.

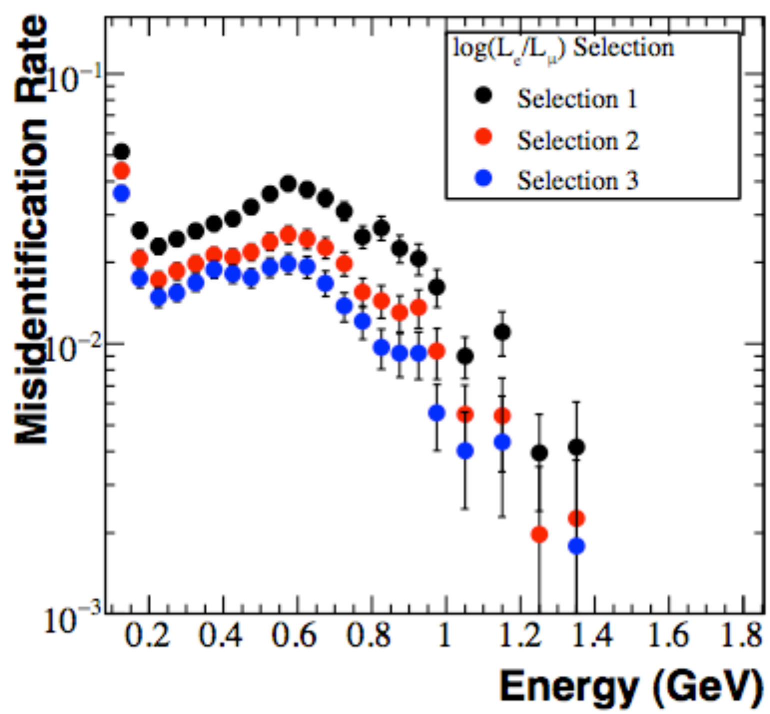
- Similar strategies for testing single, double, and multiple-ring hypotheses

# Achieved Performance of MiniBooNE Reconstruction

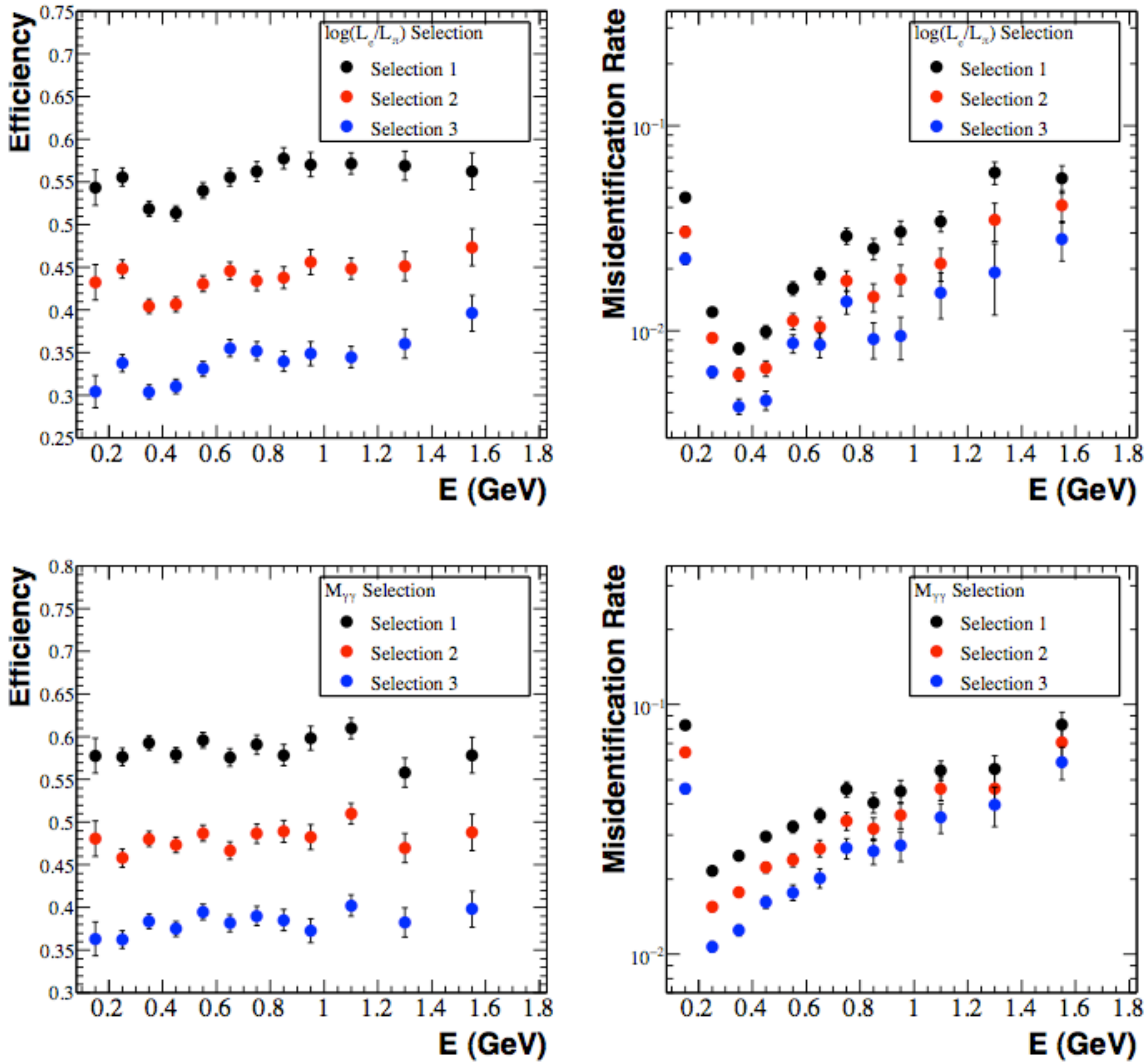
- CC QE $\nu_\mu$ events: 10 cm vertex resolution,
  8% energy resolution
  2° angular resolution
- CC QE $\nu_e$ events: 20 cm vertex resolution,
  12% energy resolution

- $\nu_\mu$ misidentification rate as $\nu_e$ ~2% for 65% efficiency



# Electron – Pizero Separation in MiniBooNE



# BONSAI – A Low-Energy Neutrino Vertex Fitter for SK

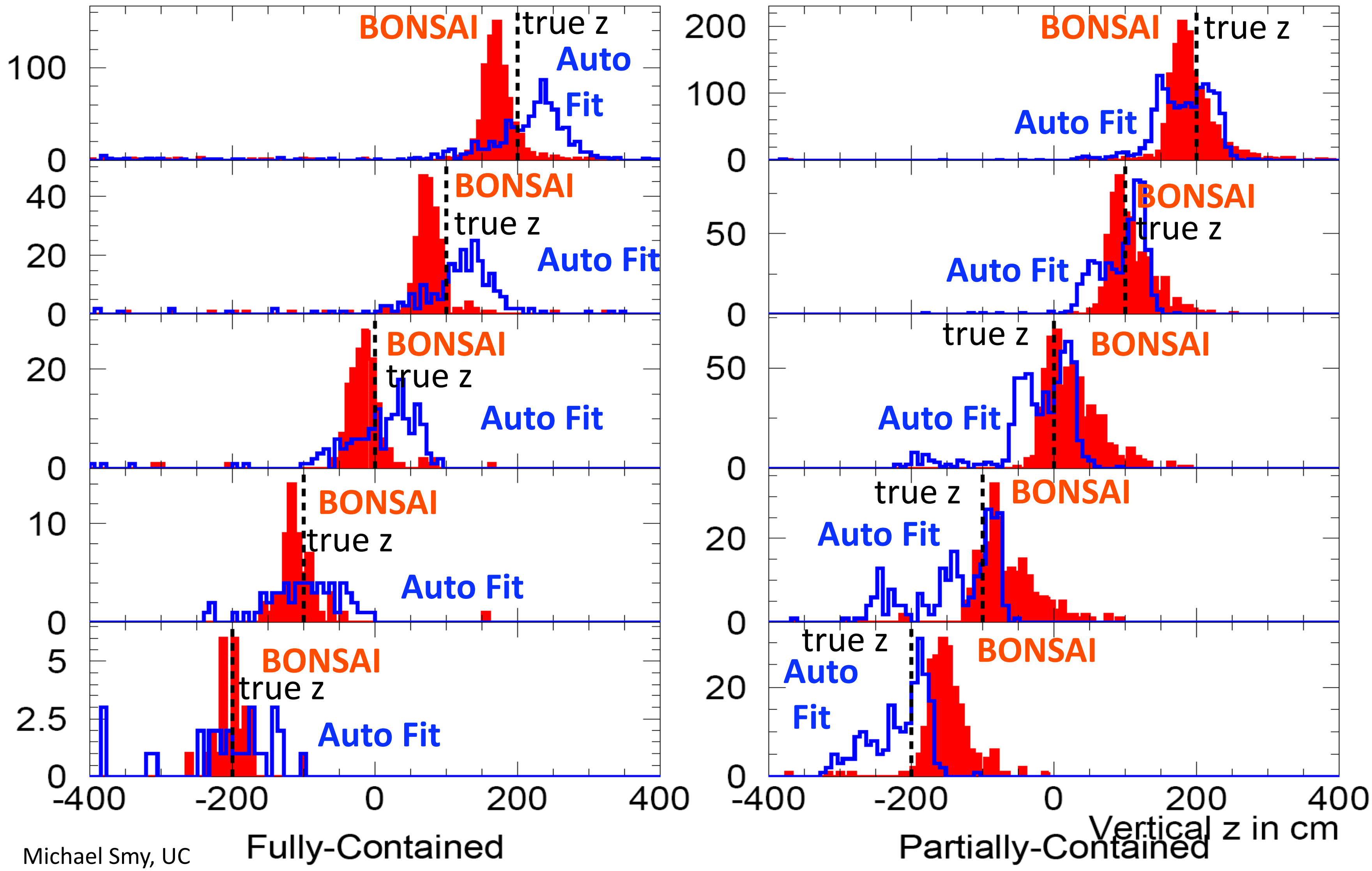
M. Smy

- Maximum Likelihood fit based almost entirely on PMT hit timing
- Can reconstruct electrons above 3 MeV
- The main issue few PMT hits, ring identification algorithms not appropriate
- Forms combinations of four hits at a time and solves for vertex position
- Event momentum direction determined with a Hough transform
- Works for high-energy events too

- Performance:

| | Supernova inverse beta neutrinos | Supernova elastic scattering neutrinos |
|---|---|---|
| Vertex resolution: | 53 cm | 80 cm |
| Direction resolution: | 16° | 25° |

# Test with “1kt” Calibration Muons




Michael Smy, UC Irvine

# Summary and Outlook

- Water/Oil Cherenkov neutrino detection is a mature technology
- Reconstruction algorithms work very well. Reconstruction efficiency ~95%, mis-ID ~0.1% (muons as electrons), <5% pizeros as electrons
- Reconstruction techniques scale to arbitrary size detectors – should be possible to reconstruct Hyper Kamiokande events with straightforward adaptation of the likelihood fitting algorithms.
- The business of reconstructing events based on light collection is very active! Lots of recent work I didn't mention:
    - Photon reconstruction in Liquid Argon detectors
    - Precision timing reconstruction – See Matt Wetstein's talk
    - CHROMA – see Stan Seibert's talk

# Extra Slides

# Marc Bergevin's Midpoint Algorithm

## Mid-Point Pair Transform

- Applied on a continuous circle

With the parameterization:

$$r = \sqrt{R^2 - \rho^2}$$

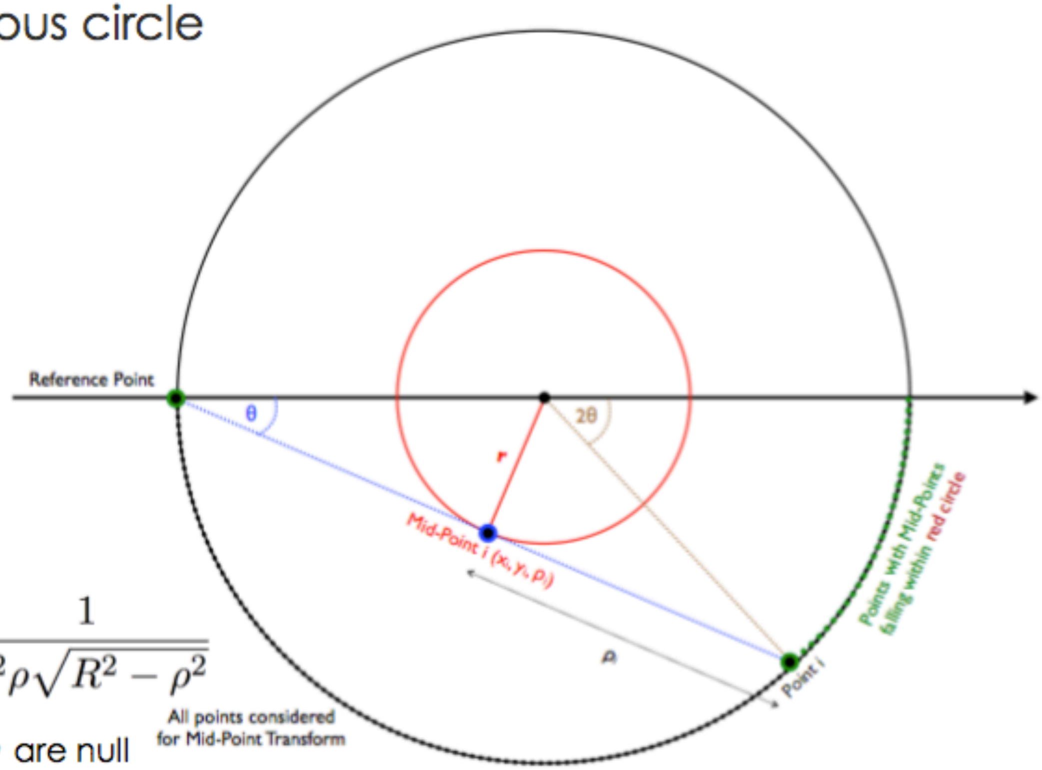
the density in the Hough space:

$$\int_0^r 2\pi r' \sigma(r') dr' = \frac{2\theta}{\pi}$$

Solving for $\sigma$:

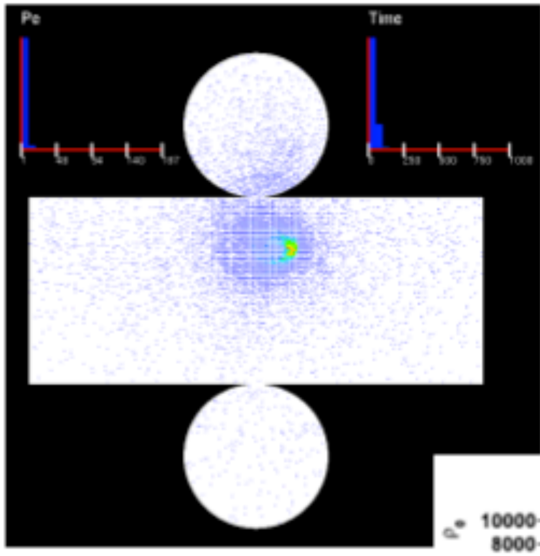
$$\sigma(r) = \frac{1}{\pi^2 r \sqrt{R^2 - r^2}} \quad \textbf{or} \quad \sigma = \frac{1}{\pi^2 \rho \sqrt{R^2 - \rho^2}}$$

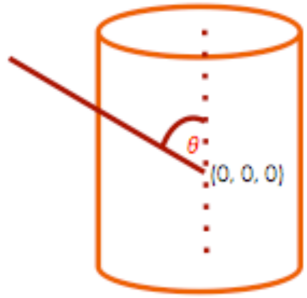
The density diverges for both $r$ and $\rho$ are null (**center of the ring** and **at the periphery**)

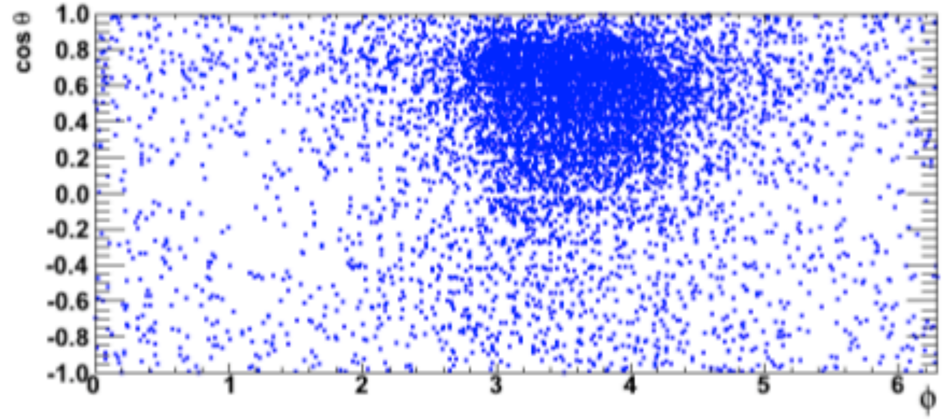


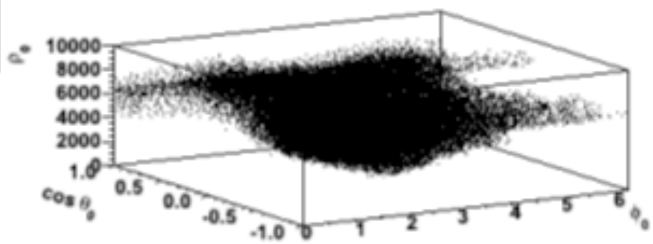
# Marc Bergevin's Midpoint Algorithm

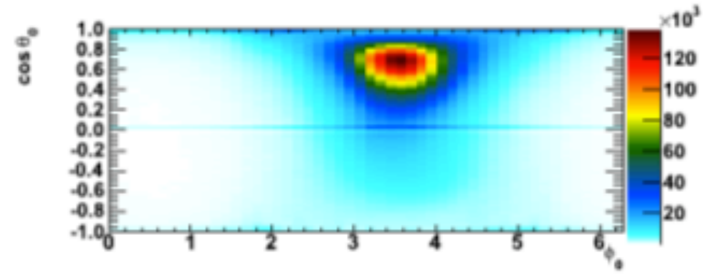
## LBNE Implementation



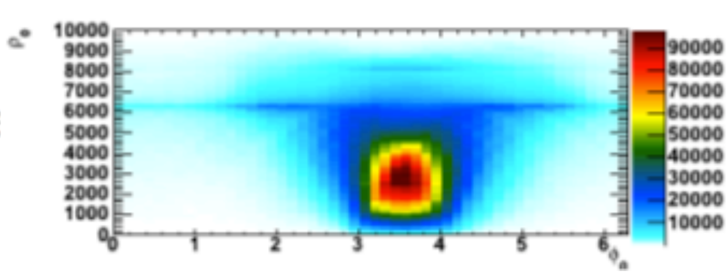



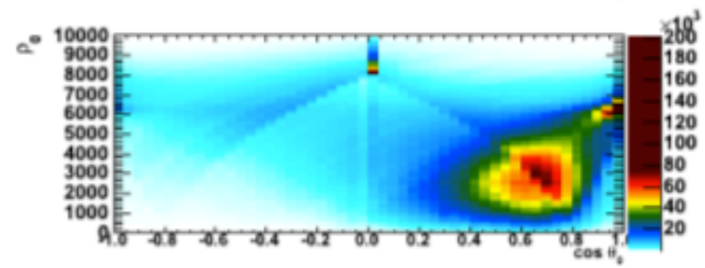



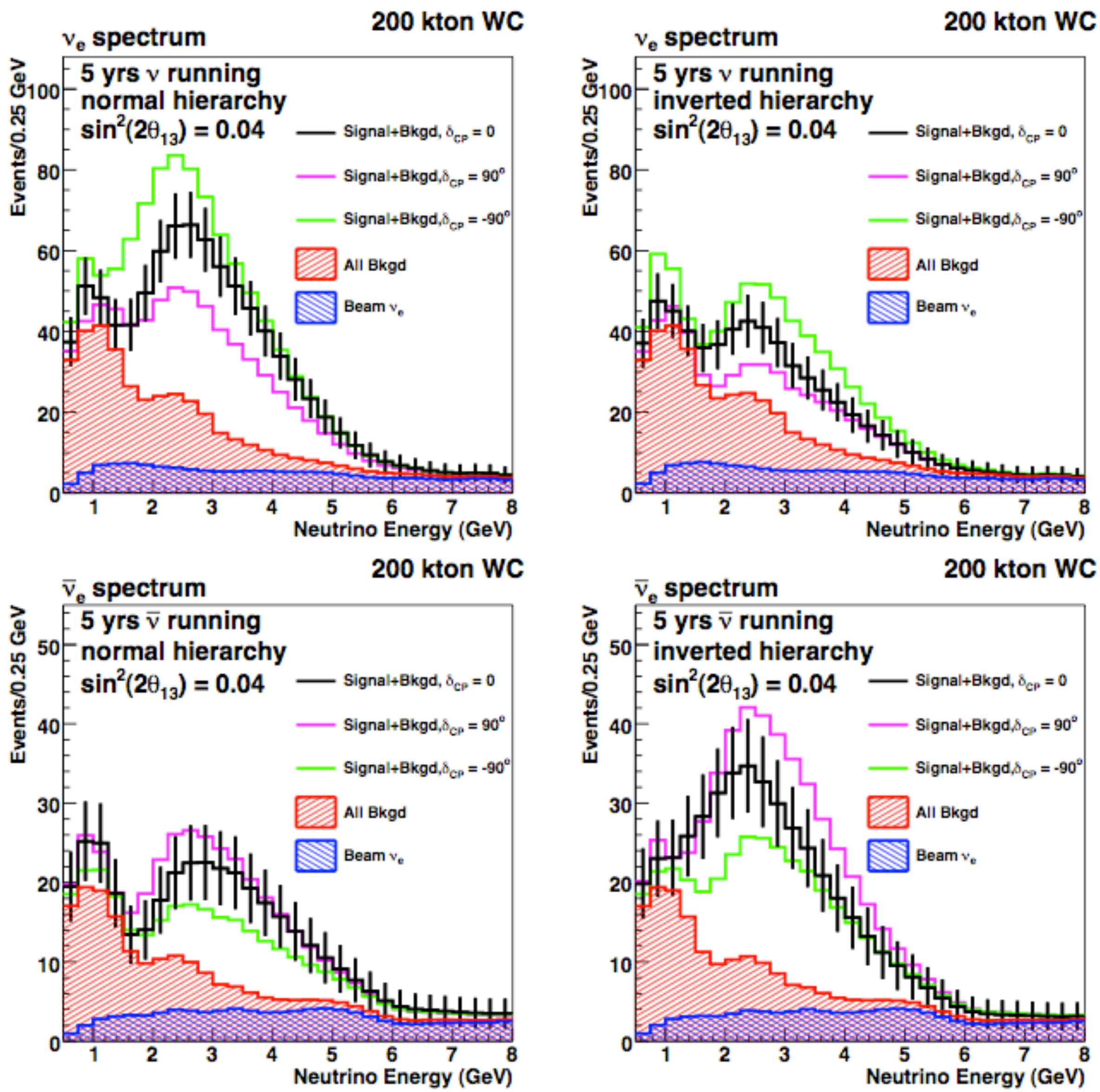


Hough Space





# Expected Spectra in a 200 KTon WC Detector at Homestake



# LBNE Proton Decay Sensitivity Extrapolation with a Water Cherenkov Detector